Which is the flavor of cosmic neutrinos seen by IceCube?

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We analyze the high-energy neutrino events observed by IceCube, aiming to probe the initial flavor of cosmic neutrinos. We study the track-to-shower ratio of the subset with energy above 60 TeV, where the signal is expected to dominate and show that different production mechanisms give rise to different predictions even accounting for the uncertainties due to neutrino oscillations. We include for the first time the passing muons observed by IceCube in the analysis. They corroborate the hypotheses that cosmic neutrinos have been seen and their flavor matches expectations.

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I. INTRODUCTION

The search for High Energy Starting Events (HESE) in IceCube detector provided the first evidence for a high-energy neutrino flux of extraterrestrial origin [1–3]. In three year of data taking [1], 37 events with deposited energies above 30 TeV were observed, relative to an expected background of 8.4 ± 4.2 cosmic ray muon events and $6.6{\pm}5.9$ atmospheric neutrinos.

The scientific debate about the origin of these events is extremely lively. There is little doubt that cosmic neutrinos have been seen, but their origin and propagation is not understood. In order to proceed, the flavor composition has to be probed. The flavor discrimination is, in principle, possible by looking at the topology of the events. Most HESE have 'shower' topology, that includes neutral current (NC) interactions of all neutrino flavors and charged current (CC) interactions of $\nu_{\rm e}$ and ν_τ, being the decay length of the τ lepton too short to be resolved below $\sim$ 1PeV. On the other hand, events with 'track' topology are produced by CC interactions of ν_μ. Thus, the crucial observable quantity is the ratio between track and shower events at high energy and it can be used to confirm the cosmic origin and/or to discriminate among different production scenarios. With this purpose the authors of [4, 5] recently discussed the observed track-to-shower ratio of the IceCube data with energy above 30 TeV claiming that these data are marginally compatible with the hypothesis that neutrinos are of cosmic origin. These studies have been influential, setting the case for a muon deficit problem in IceCube, see e.g. [6, 7].

In view of the importance of this issue, we perform an independent analysis adding our contribution to the discussion. We focus on the subset of events with deposited energy above 60 TeV, where the signal is expected to dominate. We show that different production mechanisms give rise to distinctive expectations of the track-to-shower ratio, even when the uncertainties due to neutrino oscillations are included. Also the muon neutrinos passing through the Earth confirm the existence of an astrophysical component and we include for the first time this information on the analysis. We find that present data set is well compatible with the hypothesis that cosmic neutrinos have been seen, even if the limited statistics does not allow yet to discriminate the initial flavor.

II. EXPECTATIONS

From neutrinos to HESE events. Let us consider HESE events with energies between 60 TeV to 3 PeV and starting inside IceCube, that are likely to be dominated by the signal due to cosmic neutrinos. The expected number of events produced by an isotropic flux Φ_ℓ of neutrinos and antineutrinos with flavor ℓ is,

$$N = 4\pi\, T \int dE\ \Phi_\ell(E)\, A_\ell(E) \tag{1}$$

where $\ell = e, \mu, \tau$ and T is the observation time. The effective areas $A_\ell(E)$ are provided by the IceCube collaboration [3] and include the effects of neutrino cross sections, partial neutrino absorption in the earth, detector efficiency and specific cuts of the HESE analysis.

In order to calculate the track-to-shower ratio, we separate the different contributions to the effective areas,

$$A_\mu(E) = A^{\rm T}_\mu(E) + A^{\rm S}_\mu(E) \tag{2}$$

where $A^{\rm T}_\mu(E) \equiv p_{\rm T}(E)\, A_\mu(E)$ is the effective area for ν_μ CC interactions that produce tracks in the detector, while $A^{\rm S}_\mu(E) \equiv (1 - p_{\rm T}(E))\, A_\mu(E)$ is the effective area for neutral current (NC) interactions that are instead observed as showers. The parameter $p_{\rm T}(E)$ is the probability that an *observed* event (i.e. passing all the cuts in the HESE analysis) produced by a muon neutrino with energy E is a track event. This quantity is given by,

$$p_{\rm T}(E) = \frac{\sigma_{\rm CC}(E)\, M^{\rm CC}_\mu(E)}{\sigma_{\rm NC}(E)\, M^{\rm NC}(E) + \sigma_{\rm CC}(E)\, M^{\rm CC}_\mu(E)}$$

where $\sigma_{\rm CC}(E)$ and $\sigma_{\rm NC}(E)$ are the cross section for CC and NC interactions of neutrinos [8] while $M^{\rm CC}_\mu(E)$ and $M^{\rm NC}(E)$ are the effective detector mass for CC and NC interactions of ν_μ [3]. The probability $p_{\rm T}$ is mildly dependent on energy and approximately equals 0.8.

The number of showers $N_{\rm S}$ and tracks $N_{\rm T}$ in the IceCube detector can be then calculated according to:

$$N_{\rm S} = 4\pi\, T \int_0^{\overline{E}} dE\ \{\Phi_e(E)\, A_e(E) + \Phi_\tau(E)\, A_\tau(E) + \\ +\ \Phi_\mu(E)\ [1 - p_{\rm T}]\ A_\mu(E)\}$$

$$N_{\rm T} = 4\pi\, T \int_0^{\overline{E}} dE\ \Phi_\mu(E)\, p_{\rm T}\, A_\mu(E) \tag{3}$$

In the above relation, we neglected the small fraction of ν_τ CC-events followed by taus decaying into muons which can be potentially observed as tracks. Moreover, we introduced an upper integration limit at $\overline{E} = 3\,\mathrm{PeV}$ since the HESE analysis only includes events with deposited energy below $3\,\mathrm{PeV}$. In principle, the effects of the threshold at $E_{\rm dep} = 3\,\mathrm{PeV}$ should be implemented as a correction of the effective areas. Here, we assume that this can be mimicked by a sharp cut in the $A_\ell(E)$ at the neutrino energy $E = 3\,\mathrm{PeV}$. We tested the validity of this approach by comparing our predictions with the expected numbers of events in Supp. Tab. IV of [1]. We obtain good agreement both for the absolute and relative numbers of shower and track events.

Description of cosmic neutrinos. Cosmic neutrinos are surely due to non-thermal processes. Thus we expect that their fluxes averaged over the directions, are approximated by a power law distributions up to a maximum value that we assume being larger than 3 PeV,

$$\Phi_\ell(E) = \frac{F_\ell \cdot 10^{-8}}{\mathrm{cm^2\ s\ sr\ GeV}} \cdot \left(\frac{\mathrm{GeV}}{E}\right)^\alpha \tag{4}$$

where the factors F_ℓ are (non-negative) adimensional coefficients and α is the spectral index. We use the value $\alpha = 2$, expected on theoretical basis, and find the following expressions for number of shower and track events,

$$N_{\rm S} = 8.4 \times F_e + 0.9 \times F_\mu + 6.3 \times F_\tau$$

$$N_{\rm T} = 3.7 \times F_\mu \tag{5}$$

The track-to-shower ratio is then,

$$\frac{N_{\rm T}}{N_{\rm S}} = \frac{\xi_\mu}{2.3 - 2.0\,\xi_\mu - 0.6\,\xi_\tau} \tag{6}$$

where we introduced the *flavor fractions at Earth* (i.e., in the detection point), defined as:

$$\xi_\ell \equiv F_\ell / F_{\rm tot} \tag{7}$$

with $F_{\rm tot} = F_e + F_\mu + F_\tau$, and we considered that $\xi_e = 1 - \xi_\mu - \xi_\tau$. The numerical coefficients of eq. (6) depend mildly on the spectral index, as quantified later.

The effect of neutrino oscillations. For neutrinos travelling over cosmic distances, the simplest regime (Gribov-Pontecorvo's [9]) applies and the oscillation probabilities $P_{\ell\ell'}$ are energy independent. The flavor fractions at Earth are thus given by

$$\xi_\ell = \sum_{\ell'} P_{\ell\ell'}\, \xi^0_{\ell'} \quad \text{with} \quad P_{\ell\ell'} = \sum_{i=1,3} |U^2_{\ell i}\ U^2_{\ell' i}|,$$

where U is the neutrino mixing matrix and ξ^0_ℓ are the *flavor fractions at the source* given by:

$$\xi^0_\ell \equiv F^0_\ell / F_{\rm tot} \tag{8}$$

where F^0_ℓ indicates the adimensional flux normalizations before oscillations–see eqs. (4,7). It is generally expected, see e.g. [10–12] that a cosmic population is characterized by a flavor content $(\xi_e : \xi_\mu : \xi_\tau) \sim (1/3 : 1/3 : 1/3)$ independently on the specific production mechanism. In this case, the track to-shower ratio in IceCube is,

$$\frac{N_{\rm T}}{N_{\rm S}} = 0.24 \tag{9}$$

as can be calculated from eq. (5). If we consider a spectral index $\alpha \neq 2$, this prediction is only marginally affected being approximately $N_{\rm T}/N_{\rm S} = 0.24 + 0.08\,(2-\alpha)$.

The equipartition of neutrino flavors at Earth is, however, only an approximation which is no longer adequate after IceCube data: A certain imprint of the neutrino production mechanism does remain. It is important to exploit the track-to-shower ratio observed by IceCube to discriminate neutrino origin. To explore this possibility on realistic grounds, it is necessary to quantify the relevance of uncertainties in oscillation parameters for the predictions of $N_{\rm T}/N_{\rm S}$. We note that the probabilities $P_{\ell\ell'}$ have a non-linear dependence on the neutrino oscillation parameters and, as a consequence, the errors in θ_{12}, θ_{13}, θ_{23} and δ cannot be propagated linearly. Moreover, the allowed regions for θ_{23} and δ parameters have complicated structures that cannot be correctly described by assuming gaussian dispersions with the quoted 1σ errors. We overcame these difficulties by constructing likelihood distributions of $\sin^2\theta_{12}$, $\sin^2\theta_{13}$, $\sin^2\theta_{23}$ and δ from the $\Delta\chi^2$ profiles given by [13]. Namely, we assume that the probability distributions of each parameter are provided by $\mathcal{L} = \exp\left(-\Delta\chi^2/2\right)$. Then, we combine the various likelihood functions assuming negligible correlations and we determine the probability distributions of $N_{\rm T}/N_{\rm S}$ by MonteCarlo extraction of the oscillation parameters. We consider four specific assumptions for the flavor composition at the source $(\xi^0_e : \xi^0_\mu : \xi^0_\tau)$ which are relevant for the interpretation of observational data because related to specific production mechanisms. We consider
i) $(1/3 : 2/3 : 0)$ for π decay (yellow);
ii) $(1/2 : 1/2 : 0)$ for *charmed mesons* decay (blue);
iii) $(1 : 0 : 0)$ for β decay of *neutrons* (green);
iv) $(0 : 1 : 0)$ for π decay with *damped muons* (red),
where we made reference to the color code used in Fig. 1.

Fig. 1 summarizes our results. The left panel is obtained by using the distribution of the oscillation parameters corresponding to the assumption of normal hierarchy (NH), while the right panel corresponds to the case of inverse hierarchy (IH). We see that $N_{\rm T}/N_{\rm S}$ distributions are well separated when different neutrino production mechanisms are considered. This means that a precise determination of $N_{\rm T}/N_{\rm S}$ could provide hints on the neutrino origin, even with the present knowledge of neutrino

mixing parameters. From the neutrino physics point of view, large contributions to $N_\mathrm{T}/N_\mathrm{S}$ dispersions are provided by the δ and θ_{23} parameters. Finally, our results indicates that the flavor composition of cosmic neutrinos cannot be used to learn about neutrinos, unless the neutrino production mechanism is independently identified.

For the purposes of our discussion, it is finally important to note that the track-to-shower ratio has a limited range of possible values, if neutrinos have cosmic origin. If we take the best fit oscillation parameters and assume a spectral index $\alpha = 2$, we obtain

$$0.15 < \frac{N_\mathrm{T}}{N_\mathrm{S}} < 0.30 \quad \text{[expected from cosmic origin]} \tag{10}$$

The minimal value, obtained for neutron-decay (i.e. $\xi^0_\mu = \xi^0_\tau = 0$ and $\xi^0_e = 1$), matters for the claims of a possible muon deficit problem in IceCube. If we vary the spectral index, this interval shifts by $\sim \mp 10\%$. The oscillation parameters affect slightly these expectations; e.g. for the lowest (resp. highest) value of $\sin^2\theta_{23} = 0.385$ (resp. =0.644) [13], the interval of Eq. (10) narrows to [0.16,0.27] (resp., widens to [0.09,0.43]).

III. DATA ANALYSIS

General considerations. In the energy window $60\,\mathrm{TeV} < E_\mathrm{dep} < 3\,\mathrm{PeV}$, 20 events have been observed, consisting of 16 showers and 4 tracks events, against an expected background of $\sim$ 3 events from atmospheric muons and neutrinos. By performing a likelihood fit, an isotropic astrophysical component with E^{-2} spectrum and flavor composition (1/3 : 1/3 : 1/3), as expected due to neutrino flavor oscillations (see e.g. [10–12]), is extracted at $5.7\,\sigma$ confidence level [1]. Namely, the best fit astrophysical neutrino flux is given by $E^2\,\Phi_\ell(E) = (0.95 \pm 0.3) \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, where the index $\ell = e, \mu, \tau$ refers to the neutrino flavor.

New data and analyses confirm the evidence for a cosmic neutrino population. Recently, a new technique was developed that permits to isolate events starting in the IceCube detector down to $\sim$ 1TeV and to observe astrophysical neutrinos (in the southern sky) with energies as low as 10 TeV [2]. Even more interesting, an independent analysis of the spectrum of muon neutrinos passing through the Earth has confirmed the existence of an astrophysical component. Analyzing the same period of the HESE analysis, an excess of high energy muon tracks is observed, that was fitted by assuming an astrophysical muon neutrino flux equal to $E^2\,\Phi_\mu(E) = (1.01 \pm 0.35) \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$ [14, 15].

The track-to-shower ratio. The set of events observed by IceCube in three years of data taking between 60 TeV and 3 PeV consists of a total number of $n_\mathrm{T} = 4$ tracks and $n_\mathrm{S} = 16$ showers. These includes on average $b_\mathrm{T} = 2.1$ and $b_\mathrm{S} = 0.7$ background events expected from atmospheric neutrinos (1.7 tracks and 0.7 showers) and muons (0.4 tracks and no showers) [1]. In the above estimates, we assume that the prompt atmospheric neutrinos give negligible contributions, as it required by the spectral and arrival angles distributions of IceCube events. The number of tracks N_T and showers N_S which have to be ascribed to cosmic sources can be estimated from the Poisson likelihood functions: $\mathcal{L}(N_\mathrm{i}) \propto \lambda_\mathrm{i}^{n_\mathrm{i}} \times e^{-\lambda_\mathrm{i}}$ where $\lambda_\mathrm{i} = N_\mathrm{i} + b_\mathrm{i}$ and the index $\mathrm{i} = \mathrm{T}, \mathrm{S}$ is used to refer to track and shower events. By using the above data, we obtain $N_\mathrm{T} = 3.1 \pm 2.1$ and $N_\mathrm{S} = 16.3 \pm 4.1$. Marginalizing over the total number of events, we reconstruct the track-to-shower ratio of cosmic neutrino obtaining

$$\frac{N_\mathrm{T}}{N_\mathrm{S}} = 0.11^{+0.23}_{-0.05} \quad \text{[HESE only]} \tag{11}$$

where the error was obtained by integrating out symmetrically $(1 - \mathrm{CL})/2$ on both sides of the $N_\mathrm{T}/N_\mathrm{S}$ distribution using a confidence level CL = 68.3%. The above result can be compared with the range given in eq. (10) and shows that IceCube results do not contradict the assumption of a cosmic neutrino population. The large error in the reconstructed $N_\mathrm{T}/N_\mathrm{S}$ is due to the total number of tracks which is too low to drive any conclusions about neutrino origin. Luckily, a completely equivalent and independent information can be obtained by the recently released IceCube data on passing muons [14]. About 12 events with visible energy above 60 TeV have been observed which cannot be explained by atmospheric neutrinos and muons. In the assumption of E^{-2} neutrino spectrum, this corresponds to a flux normalization $F_\mu = 1.01 \pm 0.35$ that can be translated into a number of tracks from cosmic neutrinos by using eq. (5). We obtain $N_\mathrm{T} = 3.7 \pm 1.3$ which is perfectly compatible with the value $N_\mathrm{T} = 3.1 \pm 2.1$ obtained from the HESE analysis, but is affected by factor ~ 2 smaller error. We include also this information in our analysis by constructing a combined likelihood, given by the product of the 2 Poisson likelihoods for N_T and N_S and of the Gaussian likelihood for F_μ. We then extract the bound:

$$\frac{N_\mathrm{T}}{N_\mathrm{S}} = 0.18^{+0.13}_{-0.05} \quad \text{[all data]} \tag{12}$$

by taking into account the equivalence between F_μ and N_T expressed by eq. (5) and marginalizing with respect to the total number of events. The likelyhood distribution for the track-to-shower ratio of cosmic neutrinos is shown by the shaded region in Fig.1.

IV. DISCUSSION AND SUMMARY

Fig.1 shows clearly that: *i)* there is no tension between the present observational results and the assumption of a cosmic neutrino population, being the central observational value in the middle of the expected region; *ii)* there is no clear preference for a specific neutrino production mechanism, being the observational error comparable to the difference between the various predictions.

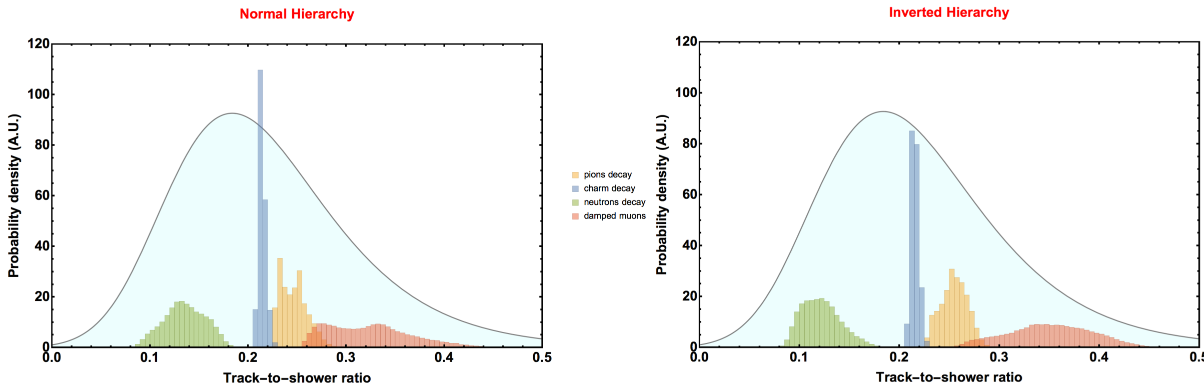

FIG. 1. *Expected track-to-shower ratio of cosmic neutrinos for the four production mechanisms described in the text. The distributions show the effect of uncertainties in the neutrino oscillation parameters. The left (resp. right) panel is obtained for normal (resp. inverse) hierarchy. The shaded region is the likelihood corresponding to Eq. (12).*

Our results are substantially different from those obtained by [4, 5]. This is partly due to the inclusion of the data on passing muons [14], partly to the fact that [4, 5] include in their analysis the HESE IceCube data between 30 TeV and 60 TeV. Following IceCube, we do not consider this region which is background dominated and much less valuable to extract the signal.

Below 60 TeV, IceCube observes 16 events, consisting of 4 tracks and 12 showers [1]. The sum of tracks and showers agrees with the expectations but there is a deficit of track events (the uncertainty on the background muon rate is, however, 50%) and an excess of shower events. If one follows [4, 5] and supposes that most of the 12 showers are due to cosmic neutrinos, then $N_{\rm S} > 50$ shower events are expected above 60 TeV [1], in severe contrast with the observational results. In other words, this position is untenable if the spectral distribution of the events, not discussed in [4], is considered. One possible explanation of the track deficit at low energy is that few ν_μ CC interactions were erroneously identified as showers since the muon track was missed (e.g., for events occurring close to the boundary of the fiducial volume). Our results, expressed by Eq. (12), are stable with respect to a possible track misidentification systematical error. Indeed, above 60 TeV, the number of expected showers is much larger than the rate of ν_μ CC interactions (and thus the erroneously identified events have a small relative importance on $N_{\rm S}$). Moreover, $N_{\rm T}$ is well estimated by passing muon data [14] which are free from track misidentification systematics.

To summarize, the HESE events observed by IceCube above 60 TeV are consistent with the hypothesis that cosmic neutrinos have been seen. The same is true for passing muon events [14]. The flux of the cosmic muon neutrinos can be determined reasonably well. The analysis of the present data gives a track-to-shower ratio, eq. (12), that agrees with that expected for a cosmic population, eq. (10). The initial neutrino flavor cannot be yet probed: indeed, all production mechanisms are allowed.

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